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21.3: Field Emission Properties of Carbon Nanotube Pillar Arrays Patterned Directly on Metal Alloy Surfaces

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Abstract: Carbon nanotube pillar arrays (CPAs) for cold field emission were fabricated using a conventional photolithography process, and the geometry of these arrays was studied and the effect of pillar height on field emission was quantified. Our CPA samples achieved turn-on fields as low as 0.9 V/μm and stable current densities of 10 mA/cm^2 at applied field lower than 6V/μm.

Introduction

Cold field emission properties of carbon nanotubes (CNTs) have been widely investigated and many applications employing CNT field emission are being developed. Stable cathodes providing high current densities at low applied fields are desirable in many applications, however they have not yet been realized due to the difficulty in controlled nanofabrication of uniform CNT films and a lack of reliable CNT cathode structures. Herein, we present novel cathode structures comprised of CNT pillar arrays (CPAs) fabricated using a commonly available and scaleable manufacturing process that allows for a high degree of control over the array geometry. This enables us to report the relationships between structure and field emission properties such as turn-on field, current density, emission area, and structural stability.

Experimental

CNT arrays were grown directly on two types of polished, ultra-smooth alloy surfaces, which eliminated any metal catalyst deposition step. To generate CPAs, conventional photolithography was employed to pattern hard masks of Cr and Mo thin films on the alloy surfaces to selectively inhibit CNT growth. Thirty-second growth on patterned 70/30 Ni/Cr substrates resulted in regular arrays of CNT films approximately 1 to 2 μm in height, as shown in Figs. **1a** and **1b**. In contrast, ten-minute growth on patterned Fe/Cr/Al alloys yielded uniform, high-aspect ratio CPAs approximately 10 to 15 μm in height, as shown in Figs. **1c** and **1d**. A CNT pillar is a localized, vertically aligned bundle of multi-walled CNTs resulting from van der Waals forces within high-density CNT growth. Pillars were only achieved with the Fe/Cr/Al Kanthal substrates in this study.

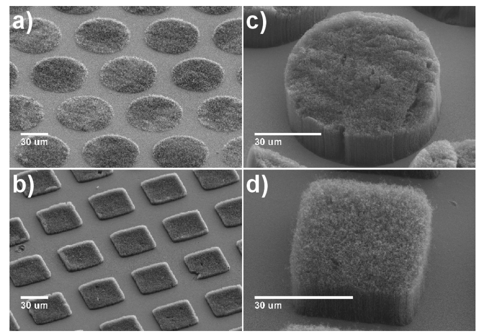

Figure 1. SEM images of patterned multi-walled carbon nanotube arrays: 30-second growth of **a)** a circular and **b)** a square patterned film array on Ni/Cr surfaces; 10-minute growth of **c)** a circular patterned and **d)** a square patterned CPA on Fe/Cr/Al (Kanthal) surfaces.

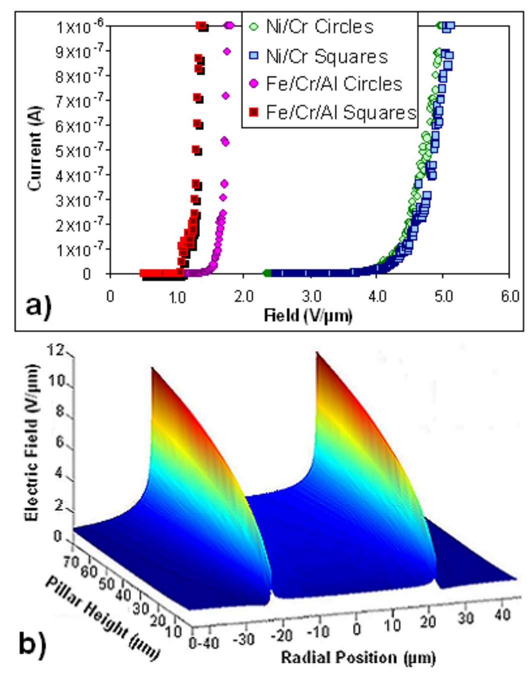

Figure 2. a) Field emission I-V plots of the four experimental cathode types. **b)** Computed electrostatic field of a pillar as a function of radial position and pillar height.

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Results and Discussion

Figure **2a** shows characteristic field emission curves for each of the four cathode types in Fig. **1**. The circle and square patterned film array samples on Ni/Cr exhibited turn-on fields (defined as the field required to draw 1 nA current) of 3.1 V/µm and 3.2 V/µm, respectively. In comparison, the circle and square CPA structures with high aspect ratios on Fe/Cr/Al exhibited turn-on fields of 1.1 V/µm and 0.9 V/µm, respectively. The dramatic reduction in turn-on fields exhibited by the high aspect-ratio CPA samples is attributed to the edge effect,[1] where the applied electric field is enhanced along the edge of each pillar. The field emission I-V data implies that pillar height significantly influences the electric field at the edges of the pillar structures.

We employed finite element electrostatic simulations to quantify this CPA edge effect. The results in Fig. **2b** show that increasing the aspect ratio of the CNT pillars magnifies the applied electric field enhancement along the edges of the structures in a highly non-linear manner. High aspect ratio CPAs show very significant field amplification, whereas low aspect ratio patterned film arrays show only moderate enhancement along the edges. To confirm this, the effective emitting areas of each sample were extracted using the linear Fowler-Nordheim[2] plots of I/V versus $\ln(I/V^2)$. The emitting areas of the high-aspect ratio CPA samples were found to be an order of magnitude smaller than the emitting areas of the low-aspect ratio patterned film array samples. This provides strong evidence that emission in the CPA samples occurred primarily from the pillar edges where the local electric field was greatly enhanced by the edge effect.

Furthermore, the CPA samples were able to emit current densities of 10 mA/cm^2 at a low applied electric field of 5.7 V/µm with less than 1% standard deviation. A field of 14 V/µm was required on average with the low-aspect ratio patterned film arrays in order to obtain the same emission current density.

We also studied the structural stability of these novel CNT cathodes in field emission. Figure **3** shows SEM images comparing pre and post-field emission cathode structures. Evidence of catastrophic microarcing was observed with the Ni/Cr samples, whereas the CPA structures on Fe/Cr/Al surfaces showed no signs of damage after field emission experiments with the same applied field. We attribute the enhanced structural and emission stability of CPAs to several factors, including increased thermal dissipation and reduced Joule heating at the CNT-substrate interfaces due to the high density CPA growth and an increased numbers of emitting sites, respectively. The increased mechanical robustness of CNT pillars compared to individual CNT emission sites is another reason for the observed structural stability of CPAs.

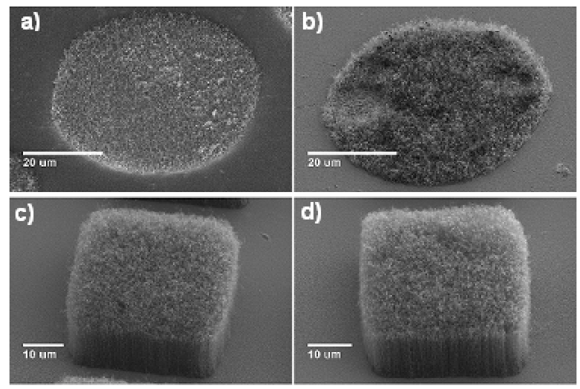

Figure 3. Patterned film array **a)** before FE, and **b)** after FE; CPA **c)** before FE, and **d)** after FE.

Conclusion

Our study has confirmed that their excellent emission characteristics and the controllability inherent in the fabrication process make CPAs one of the most promising candidates for cold field emission applications. We will also present data investigating the effects of pillar spacing and diameter on field emission and stability.

References

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